VARIABLE OPTICAL ATTENUATOR

CROSS-REFERENCE TO RELATED APPLICATIONS

[01] The present invention claims priority from United States Patent Application No. 60/398,826 filed July 29, 2002.

TECHNICAL FIELD

[02] The present invention relates to a variable optical attenuator, and in particular to a multi-port polarization independent variable optical attenuator.

BACKGROUND OF THE INVENTION

[03] Variable optical attenuators, such as the one illustrated in Figure 1 and disclosed in United States Patent No. 4,410,238 issued October 18, 1983 to Eric Hanson, include a first birefringent crystal 32 for dividing an input beam of light 36 into to orthogonally polarized sub-beams 37 and 38; a liquid crystal cell 31 for adjusting the polarization of the two sub-beams 37' and 38'; and a second birefringent crystal 33 for dividing each sub-beam 37' and 38' into orthogonally polarized components 43, 47 and 44, 48, respectively, and for recombining components 43 and 44, while spilling off unwanted light 47' and 48'. Air gaps 51 separate the first and second birefringent crystals 32 and 33 from the liquid crystal cell 31.

[04] Unfortunately, the Hanson device suffers from relatively high insertion loss as a result of poor coupling between the input and output fibers. Moreover, as a result of anisotropy in the liquid crystal, the polarization dependent loss (PDL) can also be quite significant, as the two sub-beams 37' and 38' will pass through different sections of the liquid crystal 31.

[05] An object of the present invention is to overcome the shortcomings of the prior art by providing a variable optical attenuator with better coupling between the input and the output.

[06] Another object of the present invention is to provide a variable optical attenuator with low PDL resulting from directing both of the sub-beams through the liquid crystal at the same point.

SUMMARY OF THE INVENTION

[07] Accordingly, the present invention relates to A variable optical attenuator device comprising:

[08] an input port for launching an input beam of light;

[09] a polarization beam splitter for dividing the input beam into first and second orthogonally polarized sub-beams;

[10] a first lens for collimating the first and second sub-beams, and for redirecting the first and second sub-beams along converging paths;

[11] a variable polarization rotator disposed in the crisscrossing paths for rotating the polarization of the first and the second sub-beam by a desired amount, whereby each of the first and second sub-beams has first and second orthogonally polarized components;

[12] a second lens for focusing the first and second sub-beams, and for redirecting the first and second sub-beams along substantially parallel paths;

[13] a polarization beam combiner disposed in the parallel paths for combining the first component of the first sub-beam with the second component of the second sub-beam into an output beam; and

[14] an output port for outputting the output beam.

BRIEF DESCRIPTION OF THE DRAWINGS

[15] The invention will be described in greater detail with reference to the accompanying drawings which represent preferred embodiments thereof, wherein:

[16] Figure 1 is a conventional variable optical attenuator;

[17] Figure 2 is an isometric view of a variable optical attenuator according to the present invention;

[18] Figure 3 is a polarization map of the variable optical attenuator according to Fig. 2, with full attenuation;

[19] Figure 4 is a side view of the variable optical attenuator according to Figs. 2 and 3;

[20] Figure 5 is a polarization map of the variable optical attenuator according to the present invention, with no attenuation;

[21] Figure 6 is a side view of the variable optical attenuator according to Fig. 5;

[22] Figure 7 is a side view of the variable optical attenuator according to the present invention, with partial attenuation;

[23] Figure 8 is an isometric view of an array of variable optical attenuators according to the present invention;

[24] Figure 9 is a side view of a reflected version of the variable optical attenuator according to the present invention;

[25] Figure 10 is an isometric view of another embodiment of a reflected version of the variable optical attenuator according to the present invention;

[26] Figure 11 is a top view of an array of the variable optical attenuators according to Fig. 10; and

[27] Figure 12 is a side view of the array of variable optical attenuators according to Fig. 11.

DETAILED DESCRIPTION

[28] With reference to Figures 2 to 7, the variable optical attenuator 100 according to the present invention includes a first polarization beam splitter, preferably in the form of a first birefringent crystal 101, receiving an input beam of light from an optical waveguide 102. The first birefringent crystal 101 divides the input beam of light into two orthogonally polarized sub-beams 103 and 104. For illustration purposes, sub-beam 103 is horizontally polarized, while sub-beam 104 is vertically polarized, although other variations are possible depending on the orientation of the optical axis of the first birefringent crystal 101. A first lens 106 is disposed to receive the first and second sub-beams 103 and 104 on opposite sides of the optical axis 105 thereof, whereby the first and second sub-beams 103 and 104 are redirected as collimated beams along converging paths, which crisscross and then diverge. A variable polarization rotator 107, preferably in the form of a twisted nematic liquid crystal cell, is positioned in the paths of the sub-beams 103 and 104, preferably a focal length from, i.e. in the focal plane of, the first lens 106, so that both sub-beams 103 and 104 enter the variable polarization rotator 107 at the same point, which minimizes any PDL caused by anisotropy in the liquid crystal. Depending on the mode field diameter (MFD) used and the thickness of the birefringent crystal 101, the sub-beams 103 and 104 will be very close to intersecting after passing through the first lens 106, so the PDL will be greatly reduced even if the variable polarization rotator 107 is not placed exactly at the focal plane of the lens 106. The variable polarization rotator 107, under the control of variable controller 112, changes the state of polarization (SOP) of the sub-beams 103 and 104 to a desired state depending upon the amount of output light required. The sub-beams 103 and 104, with potentially altered SOPs, exit the variable polarization rotator 107, propagate along diverging paths in collimated space, and intersect a second lens 108 on opposite sides of the optical axis 110 thereof. The second lens 108 focuses the sub-beams 103 and 104 from collimated space to converging space, and directs them along parallel paths to a polarization beam combiner, in the form

of a second birefringent crystal 109. Ideally the sub-beams 103 and 104 enter and exit the lenses 106 and 108 symmetrical with respect to the optical axes thereof 105 and 110, respectively, to enable all of the elements of the attenuator 100 to be aligned therealong. The polarization beam combiner 109 recombines the desired amount of light from each sub-beam 103 and 104 for output an output waveguide 111, while spilling-off any unwanted light.

[29] Figures 3 and 4 illustrate the variable optical attenuator 100 providing 100% attenuation. At Position A the input beam of light is illustrated as having mixed polarizations entering into the first birefringent crystal 101. By Position B, the first and second sub-beams 103 and 104 are orthogonally polarized and spatially separated. The first lens 106 redirects the first and second sub-beams 103 and 104 along paths converging to the same point of entry into the variable polarization rotator 107 (Position C). In the example given in Figure 3 and 4, the variable polarization rotator 107 provides no polarization rotation, therefore the sub-beams 103 and 104 maintain the same polarization therethrough to Position D, but with a slight spatial separation. By Position E, the sub-beams 103 and 104 have traveled along diverging paths (in collimated space) resulting in even more spatial separation. Since the states of polarization of the first and second sub-beams 103 and 104 were not altered by the variable polarization rotator 107, the first sub-beam 103 continues through the second birefringent crystal 109 parallel to the output waveguide 111, while the second sub-beam 104 is walked off away from the output waveguide 111. Accordingly, the input light is fully attenuated, as not light is directed to the output waveguide 111.

[30] Figures 5 and 6 illustrate the variable optical attenuator 100 providing no attenuation. In this example, Positions A, B and C are identical to those detailed hereinbefore. However, in this example, the variable polarization rotator 107 is set to rotate the state of polarization of both of the first and second sub-beams 103 and 104 by 90°. Accordingly, after the second lens 108 directs the first and second sub-beams 103 and 104 along parallel paths to the second birefringent crystal 109, the first sub-beam (now vertically polarized) and the second sub-beam (now horizontally polarized) are directed to the input end of the output waveguide 111.

[31] Ideally, the first and second lenses 106 and 108 are positioned equidistant from the variable polarization rotator 107, whereby the first and second sub-beams travel the same optical path length from Position B to Position E. Moreover, the first and second birefringent crystals 101 and 109 are manufactured and arranged so that the combined optical path length for the first and second sub-beams 103 and 104 traveling therethrough is equal. For simplicity, the first and second birefringent crystals 101 and 109 are made from the same material, e.g. rutile, and have the same thickness ($t_1 = t_2$). Due to the fact that the first and second sub-beams 103 and 104 travel substantially equal optical path lengths through the variable optical attenuator 100, polarization mode dispersion (PMD) is greatly limited. However, in certain instances when the device of the present invention is combined

with another optical device, the thicknesses t_1 and t_2 of the first and/or the second birefringent crystals 101 and 109 can be altered to induce PMD, and thereby cancel any PMD from the other optical device.

[32] The example illustrated in Figure 7 represents the variable optical attenuator 100 according to the present invention with an attenuation between 0% and 100%. Again, Positions A, B and C are identical to those detailed hereinbefore. However, in this case, the variable polarization rotator 107 is adjusted to rotate the polarization of the first and second sub-beams 103 and 104 by an amount greater than 0°, but less than 90°. Accordingly, the first and second sub-beams 103 and 104 exit the variable polarization rotator 107 with mixed states of polarization, i.e. with a component horizontally polarized 103h and 104h, and a component vertically polarization 103v and 104v, respectively. As a result, when the first sub-beam 103 enters the second birefringent crystal 109, the horizontal component 103h continues straight through along a path parallel to the output waveguide 111, while the vertical component 103v is directed to the input end of the output waveguide 111. Similarly, the vertical component 104v of the second sub-beam 104 is spilled off away from the input end of the output waveguide 111, while the horizontal component 104h is recombined with the vertical component 103v of the first sub-beam 103, and enters the output waveguide 111.

[33] With reference to Figure 8, another advantage of the design of the present invention is illustrated by an array of variable optical attenuators 200, which is able to use a first strip of birefringent material 201 optically coupled to an array of input waveguides 202 for splitting a series of input signals into a series of first and second sub-beams 203a to 203d and 204a to 204d. A micro lens array 206 directs the first and second sub-beams 203a to 203d and 204a to 204d through a series of variable polarization rotators, in the form of a liquid crystal array 207. A second array of micro lenses 208 directs the first and second sub-beams 203a to 203d and 204a to 204d from the diverging paths (in collimated space) to parallel paths (in converging space) for entry into a second strip of birefringent material 209. As hereinbefore discussed, the second strip of birefringent material 209 combines the desired amount of light from each input signal for output an array of output waveguides 211. Since the light from each waveguide of the input waveguide array 202 continuously travels in the same plane, as seen in Figures 4, 6 and 7, and illustrated as the middle column in Figures 3 and 5, the array of variable optical attenuators 200 can be constructed in a very compact package by positioning the plane corresponding to each input waveguide parallel to each other. As an example: an 8 mm long rutile strip having a thickness of 250 μm and a height of less that 1 mm enables an array of up to 32 fibers separated by 250um to be optically coupled.

[34] Figure 9 represents another embodiment of the present invention, in which a variable optical attenuator 300 is in a folded configuration. A birefringent crystal 301 is used to split light from an input waveguide 302 into first and second sub-beams 303 and 304, which are directed by a

first lens 306 through a variable polarization rotator 307. In this embodiment, a retro-reflective element, preferably in the form of a corner cube prism 305, is used to redirect the first and second sub-beams 303 and 304 back along paths generally parallel to their original paths, whereby a second lens 308 directs the first and second sub-beams 303 and 304 through the second birefringent crystal 309 to an output waveguide 311, which is substantially parallel to the input waveguide 302. The variable polarization rotator 307 may be positioned between the first lens 306 and the corner cube 305 or between the corner cube 305 and the second lens 308. Alternatively, the variable polarization rotator 307 may be made up of two separate liquid crystal cells, each rotating the polarization of the sub-beams by half the required amount.

[35] Figure 10 illustrates another embodiment of a reflected version of the variable optical attenuator 400, which includes a single birefringent crystal 401 for separating an input beam of light launched from input waveguide 402 into first and second sub-beams 403 and 404. The sub-beams 403 and 404 pass through a collimating lens 406 on opposite sides of one half thereof, so that the sub-beams 403 and 404 are redirected to the same spot on a liquid crystal cell 407, and so that they are incident upon the liquid crystal cell 407 with a slight angle. A reflective surface 405, positioned behind the liquid crystal cell 407, reflects the sub-beams 403 and 404 back through the other half of the lens 406 to an output waveguide 411.

[36] With reference to Figures 11 and 12, an array 500 of variable optical attenuators 400 is illustrated from the top and the side. The array 500 uses one long strip of birefringent material 501, one strip of reflective material 505, and a liquid crystal array 507 with individually controllable cells.